

RIBCAGE CHARACTERIZATION FOR FE USING AUTOMATIC CT PROCESSING

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ABSTRACT

Standard medical chest and abdominal computed tomography (CT) scans of 46 subjects were analyzed to characterize aspects of human ribcage geometry and bone density. A semi-automatic algorithm was developed to define framework curves for individual ribs. Measurements of this framework were taken to record anthropometric properties of the ribcage such as overall ribcage dimensions and individual rib lengths and angles. Furthermore, the ribcage framework was used to explore the voxel space of the CT images, recording local rib bone cross-sectional density properties. Proposals are made for the use of these measurement techniques to inform and improve human finite element (FE) chest models in terms of global geometry, material properties, and individuality.

Index terms— Ribcage, ribs, CT, bone, bone mineral density (BMD), trauma, fractures

1. INTRODUCTION

Thoracic injuries pose a major challenge in the area of motor vehicle crash safety. Studies showing an increased risk of rib fracture with age, coupled with an increasingly aged population, indicate that this issue is becoming even more important.

Low energy trauma bone fracture has been linked with lower bone mineral density (BMD), and this trend has recently been reported with high energy trauma fractures, as well [1,2]. Geometric properties of the ribcage such as rib angle have also been linked to rib fracture risk [3].

1.1. Injury prediction techniques

Current car crash dummies lack the biofidelity required in the ribcage area to predict specific injuries, while difficulties in cadaver test setup and repeatability limit such tests as predictive tools. Therefore computation methods such as human body FE modeling are seen as offering significant benefits to the study of the ribcage and the relationship between vehicle collisions and high energy traumatic injuries.

1.2. Current human models

Despite the benefits outlined above, most commercially available human FE models are currently based on a single set of human geometric and material data, usually aimed at modeling a 50th percentile American male [4,5]. A major obstacle when validating such models is that most cadaver-based test data comes from individuals with dissimilar body shapes, often vastly different from the model basis.

Some models are scaled in an attempt to represent different body shapes; however these methods are mainly based on linear scale factors obtained through physical measurement of externally visible body locations. When considering the complex 3-dimensional variation in the human ribcage, simple scaling based on external body measurements does not accurately reflect the structural variation. Additionally, simple scaling of models does not account for non-anthropomorphic variation in the population, such as changes in bone and muscle [6].

1.3. Aim and scope

This paper proposes a novel method to characterize the human ribcage directly from CT scans of the chest and abdomen. The method includes techniques for the processing of CT data to collect accurate ribcage geometry and bone density information in a consistent manner. This information can be used to inform current FE human models and improve their predictions of human kinematics and injury to the chest region.

2. METHOD

Institutional Review Board approval was obtained to utilize medical imaging studies from patients undergoing CT scanning for medical indications at the University of Michigan. Chest scans from 46 adult males were randomly selected. Scans with significant skeletal abnormalities or fractures were excluded from this study. The ages of all subjects ranged from 16 to 82. The body mass index (BMI) of all subjects ranged from 19 to 32. All subjects were lying flat on the scan-

ning table during each scan. The slice thickness of all scans ranged from 0.625mm to 2.5mm, and spatial resolution within each slice from 0.5859mm to 0.9785mm.

2.1. Initial processing

Each of the CT scans was processed using the MIMICS software package to define the geometry of the ribs, spine, and sternum using a bone tissue lower threshold of 140 Hounsfield units (HU). Volumetric meshes of the spine, sternum, and each rib were created using these geometry files

This initial processing was checked by operators to ensure separation of the spine from all rib meshes, and to ensure calcified cartilage was removed from the sternum and rib meshes.

2.2. Ribcage coordinate system

Using the volumetric meshes of the sternum and spine, a ribcage coordinate system was fitted to each ribcage. This coordinate system X-axis was defined as the anterior direction of the scanning bed. To account for misalignment between the ribcage axial direction and the scanning bed, a ribcage sagittal plane is fitted to points on the sternum and spine meshes using a least squares method. The sternum points were taken from area centroid of cross sections taken through the sternum mesh. The spine points were taken as the posteriormost points on the spinous processes of the vertebral bodies. The normal to this plane in the subject's right-to-left direction provided the ribcage Y-axis, with the Z-axis subsequently computed from the X and Y axes, as shown in Figure 1. All subsequent measurements of ribcage and rib linear dimensions were taken with respect to this fitted coordinate system.

2.3. Rib framework curves

For each separate volumetric mesh of the rib bones, a rib centroid framework curve was calculated. This 3-dimensional curve lies along the center of each rib mesh as shown in Figure 2, and was calculated using custom-built software.

Since each rib is curved in 3D space, planar cross sections of the rib do not give true representations of the cross section at any given location along the rib. To overcome this, the centroid framework curve is used to calculate a series of 25 cross sections, each one perpendicular to this framework curve. The first 10 cross sections were distributed evenly from the posterior end of the rib to 30mm beyond the tubercle, with remaining cross sections distributed evenly along the remaining length of the rib, as shown in Figure 2. The location of

the tubercle was specified using the tip of the vertebral transverse process.

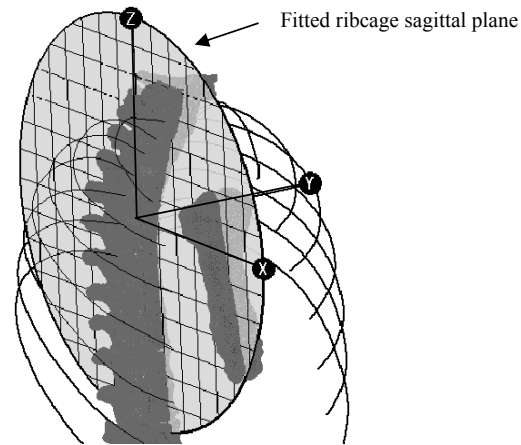


Figure 1. Ribcage coordinate system.

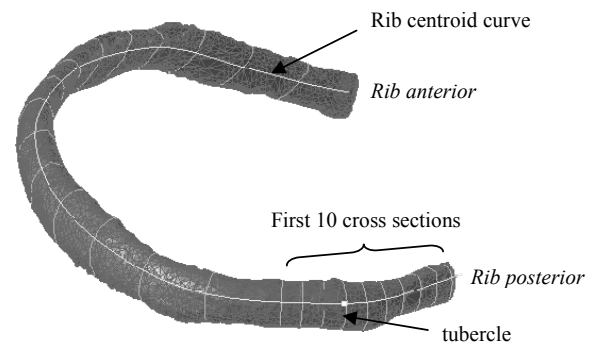


Figure 2. Rib centroid and cross section framework curves.

2.4. CT space analysis

After creating the framework curves for each rib, they are used to measure aspects of the CT voxel space. New CT values on the plane of each planar cross section curve are interpolated from the original CT data. The interpolated pixels are taken at 0.25mm spacing, using linear interpolation of the original CT voxel space.

This allows characterization of each rib cross section in terms of CT data measurements such as average HU value, and cortical and trabecular bone thickness and density.

The average HU value is calculated as the simple average intensity of all interpolated pixels on the cross section plane that lie inside the cross section boundary curve.

3. RESULTS

3.1. Recorded data

The method outlined above was completed for an initial set of 46 individual male CT scans. The extent of

these scans along the torso varied between subjects and only ribs that were fully within the scanned region were considered, producing a total of 942 analyzed ribs. Table 1 shows the number of successful measurements taken during processing for this study.

Table 1. Data points collected during processing.

Body object	Total examined
Ribcages	46
Rib pairs	469
Ribs	942
Rib X-sections	23345

3.2. Ribcage geometry

A ribcage bounding box was calculated to characterize global properties of each ribcage. The ribcage bounding box completely encloses the set of rib framework curves in each ribcage, calculated in that ribcage's coordinate system. Mean and standard deviations of the width and depth dimensions of this box for the set of scans analyzed is given below in Table 2.

Table 2. Rib cage bounding box dimensions (mm).

Body object	Measure	Avg.	Std. Dev.
Ribcage	Width	303.3	24.5
Ribcage	Depth	199.4	19.6

3.3. Rib geometry

The rib length and angle of each rib was calculated from the rib framework curves. The rib angle was determined as the angle subtended between the ribcage Z-axis and the diagonal corners of a rib bounding box as illustrated in Figure 3. Figure 4a below shows mean rib lengths, and Figure 4b shows mean rib angles from the complete data set. Whiskers on both figures indicate standard deviations from the mean.

3.4. Voxel space data

With 25 cross-sectional slices taken through each of the 942 complete ribs available in the CT scans, a database of 19,425 sections was collected. Figure 5 below shows mean HUs for rib cross sections arranged by rib number (vertical stacking) and rib location (horizontal stacking), with left and right rib results combined. Figure 6 shows the mean HU taken from the third left rib at the 15th cross section location, plotted against subject age, along with a trend line to show the decline by age.

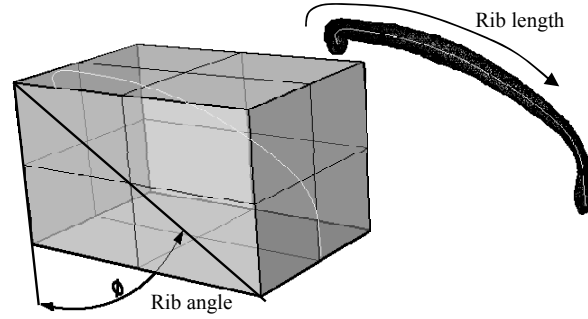


Figure 3. Rib length and angle measurement. Rib bounding box is taken in the ribcage coordinate system.

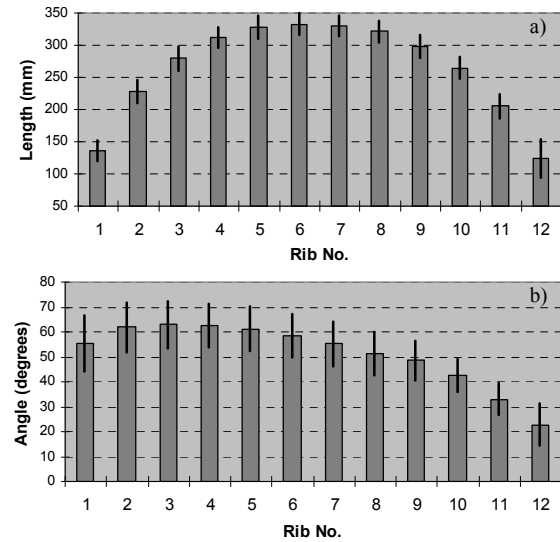


Figure 4. Mean rib lengths (a) and angles (b) by rib level.

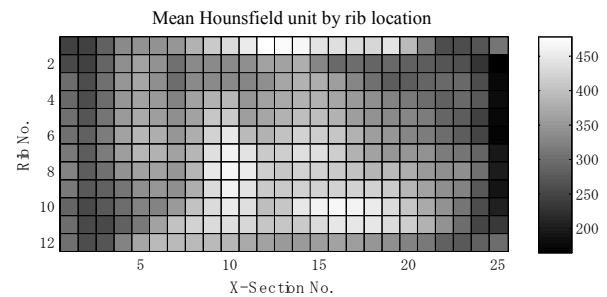


Figure 5. Rib cross-sectional mean HU values. Patches represent ribs 1 to 12 (vertically from top) and rib posterior to anterior (horizontally from left).

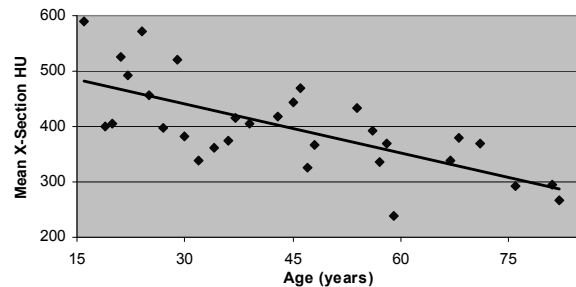


Figure 6. 3rd left rib, 15th cross-sectional HU average values plotted against age.

4. DISCUSSION

The results for rib length and rib angle show how these measures change as a function of rib level, distributed from the 1st to 12th levels. The results for rib cross-sectional average HU values provide an indication of the local geometry and material changes present along human ribs. Secondly the results highlight the importance of considering target age when creating FE models.

4.1. Method applications

Global results such as ribcage width and depth, along with individual rib lengths and rib angles are based on the internal bone geometry of individual subjects. This offers significant advantages over traditional measures used for model scaling, which are primarily based on physical measurements of external body regions performed by hand. As such, this method is ideal for scaling of standard FE human models to match the geometries of individuals used in specific cadaver tests.

A previous study of 700 subjects has identified a relationship between age and rib angle, showing a significant difference between subjects under 40 and over 55 years of age, measured at ribs 9 and 10 by operators visually inspecting CT scans [3]. The methods outlined in this study offer automatic and accurate data collection methods for such studies with minimal capacity for operator error.

Furthermore, parametric studies of rib angle in human FE models placed in tabletop compression tests have shown an increase in effective thoracic stiffness as the ribs become more perpendicular to the spine [3]. The current results for rib angle, given as mean and standard deviations over all rib levels, can be used as a guide to such parameter studies.

When considering the mechanical behavior of a rib under loading, its response is driven by the cross-sectional geometry and material properties at the area under consideration. To the authors' knowledge, localized material properties of rib cortical and trabecular bone are not modeled in current commercially available FE human models. However, material properties are often provided with associated variation in the specimens tested. It is thought that the localized results for rib cross-sectional HU values may offer a basis for scaling of the standard material data within the variation seen during testing.

4.2. Study limitations

The mean HU values of individual rib cross sections are calculated over both the cortical and trabecular regions of the cross section. Therefore, areas with higher ratios of cortical bone to trabecular bone are likely to

show higher mean HU values that do not necessarily reflect higher bone density. Studies are continuing to develop methods to reliably separate cortical from trabecular regions of rib cross sections and characterize these two regions independently.

In this study the effect of poorly calibrated CT scanners has not been considered. In future studies, such effects could be detected and overcome by including a phantom in CT scans to ensure precise CT intensities. Furthermore, the effect of changes in scan resolution and slice thickness has not been considered in this study.

5. CONCLUSIONS

This paper outlines a method to characterize the human ribcage directly from a regular chest CT scan in an automatic, accurate, and systematic manner. The characterization of the ribcage can then be used as a data source to provide relevant geometric and material data to inform human FE chest models. A sample of this data source is provided, showing a summary of ribcage size, rib lengths and angles, and mean cross-sectional HU values for rib bone cross sections.

6. REFERENCES

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